

Supernova Summary

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Speakers: Josh Klein (U Penn), Cecilia Lundardini (Arizona State), Hasan Yuksel (U of Delaware)

Comparing Liquid Argon to Water

Supernova Neutrinos

➤ Event Rates

100 kt of LAr, SN @ 10 kpc

Interaction	Rates ($\times 10^4$)
ν_e CC (${}^{40}\text{Ar}, {}^{40}\text{K}^*$)	2.5
ν_x NC (${}^{40}\text{Ar}^*$)	3.0
ν_x ES	0.1
anti- ν_e CC (${}^{40}\text{Ar}, {}^{40}\text{Cl}^*$)	0.054

100 kt H₂O, SN@10 kpc

Interaction	Rates ($\times 10^4$)
$\tau_e + p \rightarrow n + e^+$	2.3
$\tau_x + e \rightarrow n + e$	0.1
$\tau_x + {}^{16}\text{O} \rightarrow {}^{16}\text{O} + n_x$	0.05
$\tau_x + {}^{16}\text{O} \rightarrow {}^{16}\text{F} + e$	0.2

A. Bueno NP2008, via K.Scholberg

For Andromeda, multiply by 2x10⁻⁴

Talk by Josh Klein

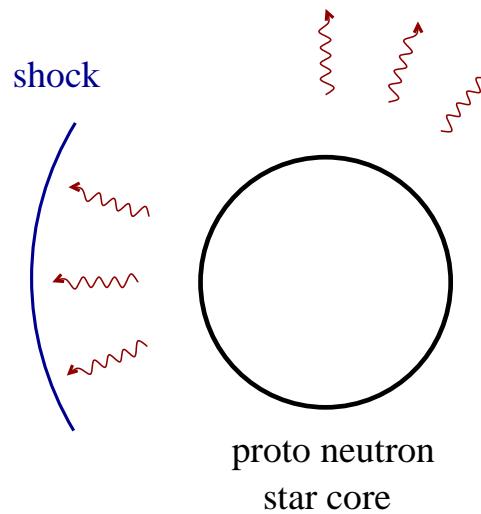
What can SN neutrinos tell us?

Something about...

- Picture of core of a supernova
- Neutrino fundamental properties
- Supernova hydrodynamics

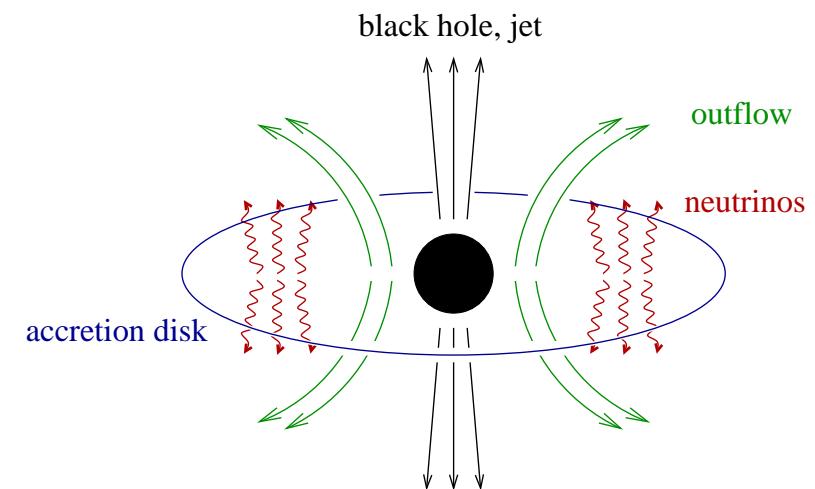
Explosions of Massive Stars:

What's happening at the center?



Standard core core collapse SN

Many, many papers

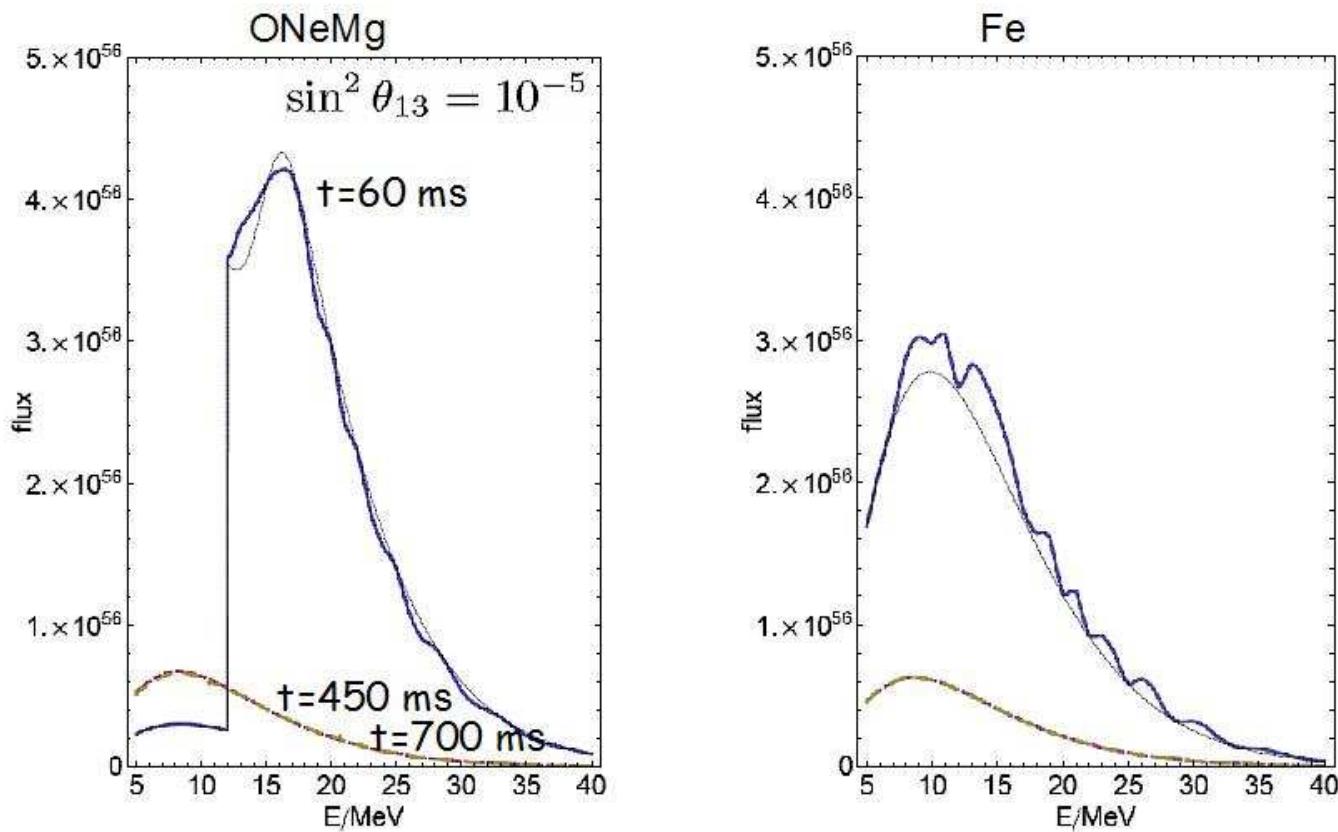


Accretion Disk SN (GRB?)

MacFadyen and Woosley 1999, Proga et al 2003, and more

What's at the core?

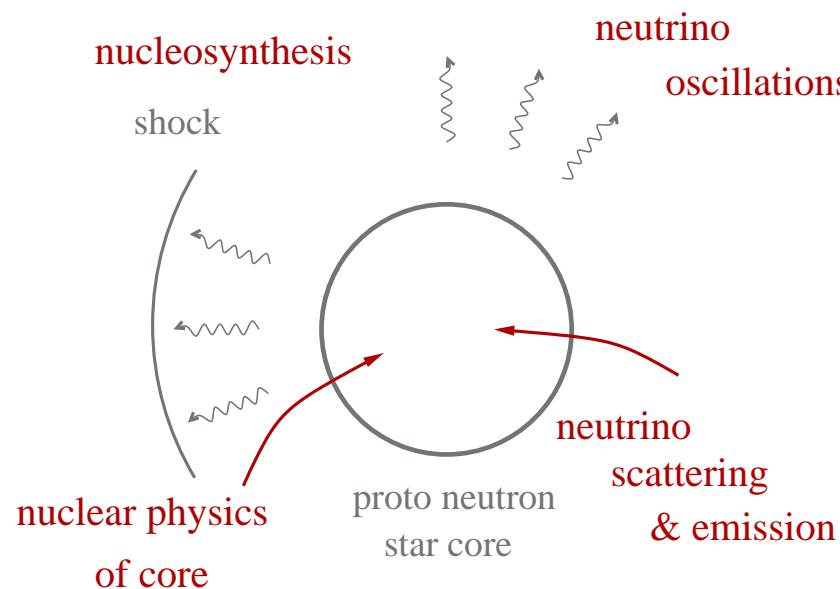
Observed spectra



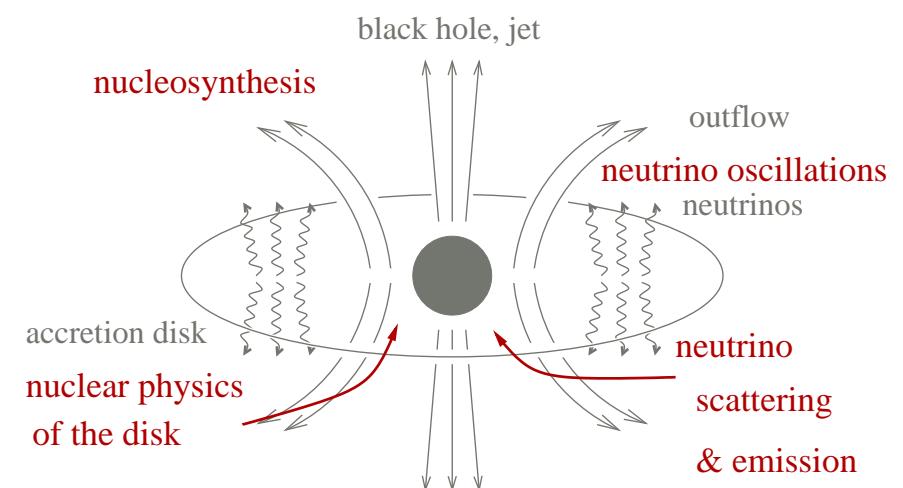
Talk by Cecilia Lundardini

Explosions of massive stars:

Where do the neutrinos fit in?



Standard core core collapse SN

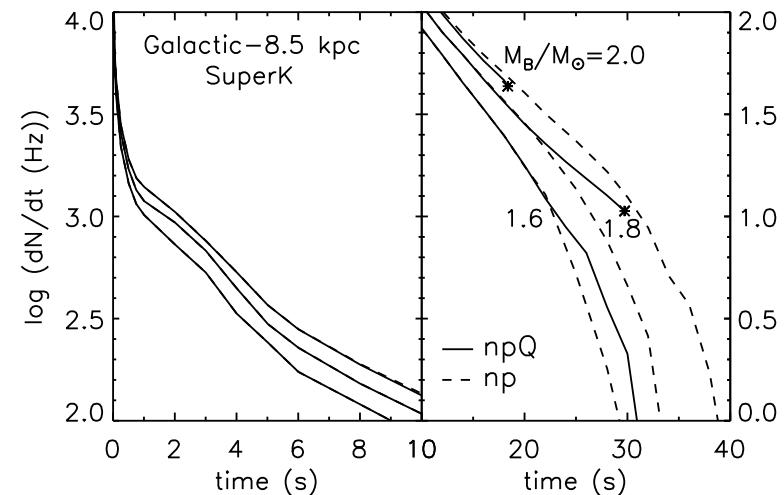


Accretion Disk SN

What can SN neutrinos probe?

Neutrinos spectra, timescales when emitted from the core

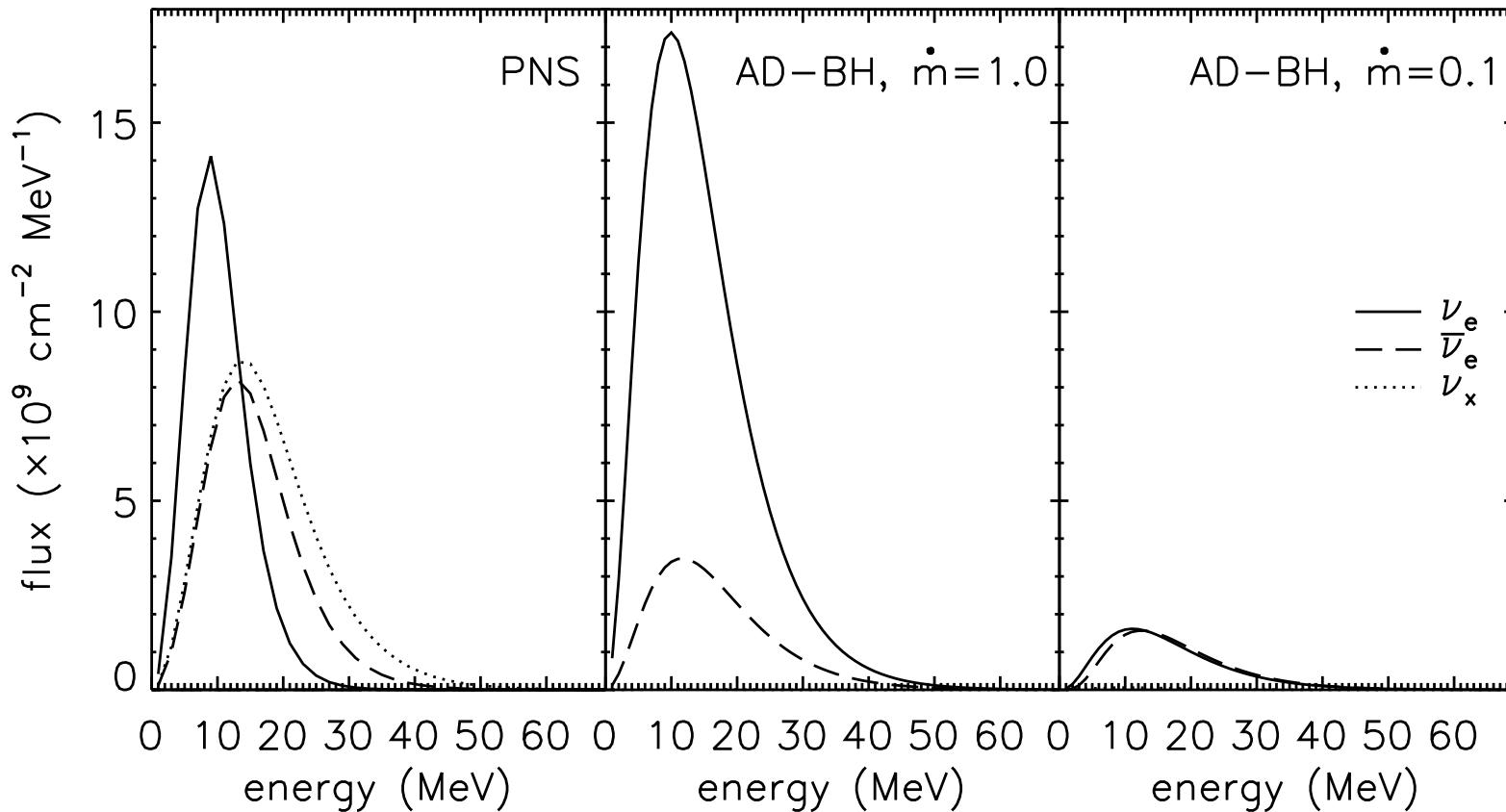
- neutrino opacities
- equation of state
- diffusion calculations



Rates in SuperK for different core masses and equations of state, Pons et al 2002

neutrino diffusion calculations: Breun, Cardall, Pons, Prakash, Janka, and more

What do these astrophysical neutrino spectra look like?



Proto-neutron star spectral parameters from Keil et al 2003, Figure from GM & Surman 2006

Neutrino flavor transformation in supernovae

Spectra measured on earth \neq emitted neutrino spectra

original $\nu_e \rightarrow$ some combination of ν_e, ν_μ, ν_τ

original $\nu_\mu \rightarrow$ some combination of ν_e, ν_μ, ν_τ

original $\bar{\nu}_e \rightarrow$ some combination of $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$

etc...

Furthermore effect is energy dependent

What can SN neutrinos probe?

Fundamental neutrino properties

- δm^2 's
- angles
- CP violation
- magnetic moment, beyond the standard model physics
- sterile neutrinos

Neutrino Flavor Transformation Calculations

Lots of activity in calculating

- resolving features of the density profile

Fuller & Schirato 2002, Fogli et al 2003, Choubey et al 2007, Tomas et al 2004, Kneller et al 2008

- including those producing finely grained phase effects

Friedland & Gruzinov 2006, Kneller et al 2006, 2008, Dasgupta & Dighe 2006

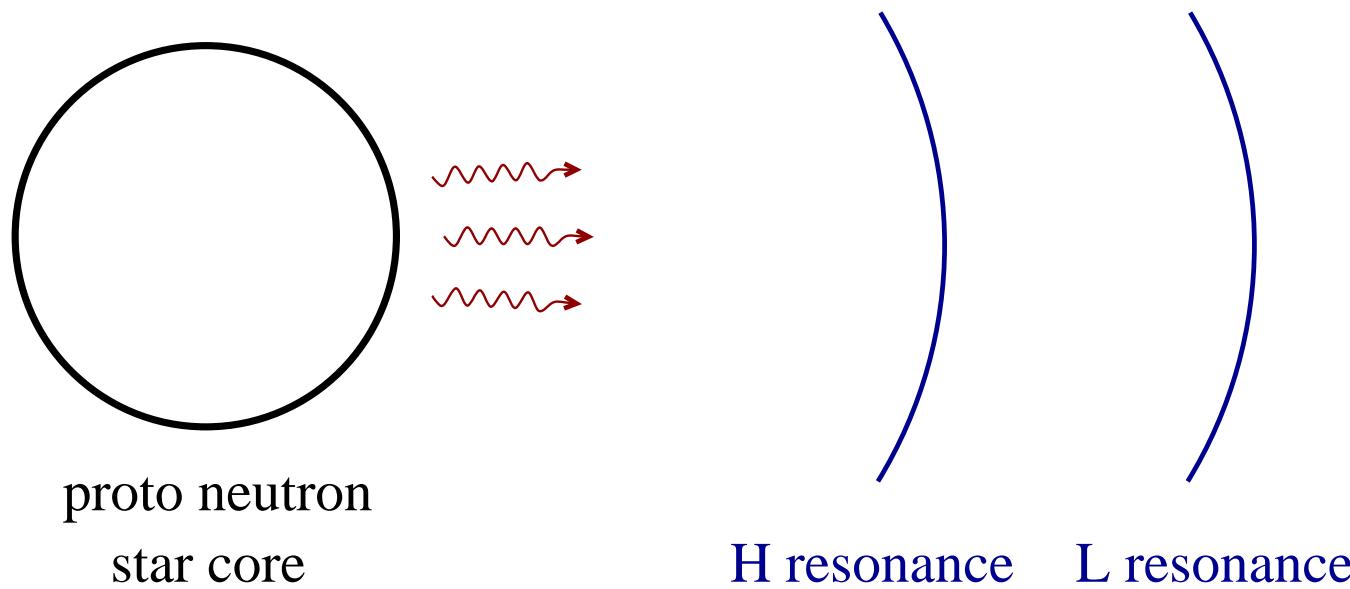
- collective effects/ swapping

Dighe, Carlson, Duan, Fuller, Gava, Mirizzi, Raffelt, Sigl, Smirnov, Volpe and more

Calculations become more technical...

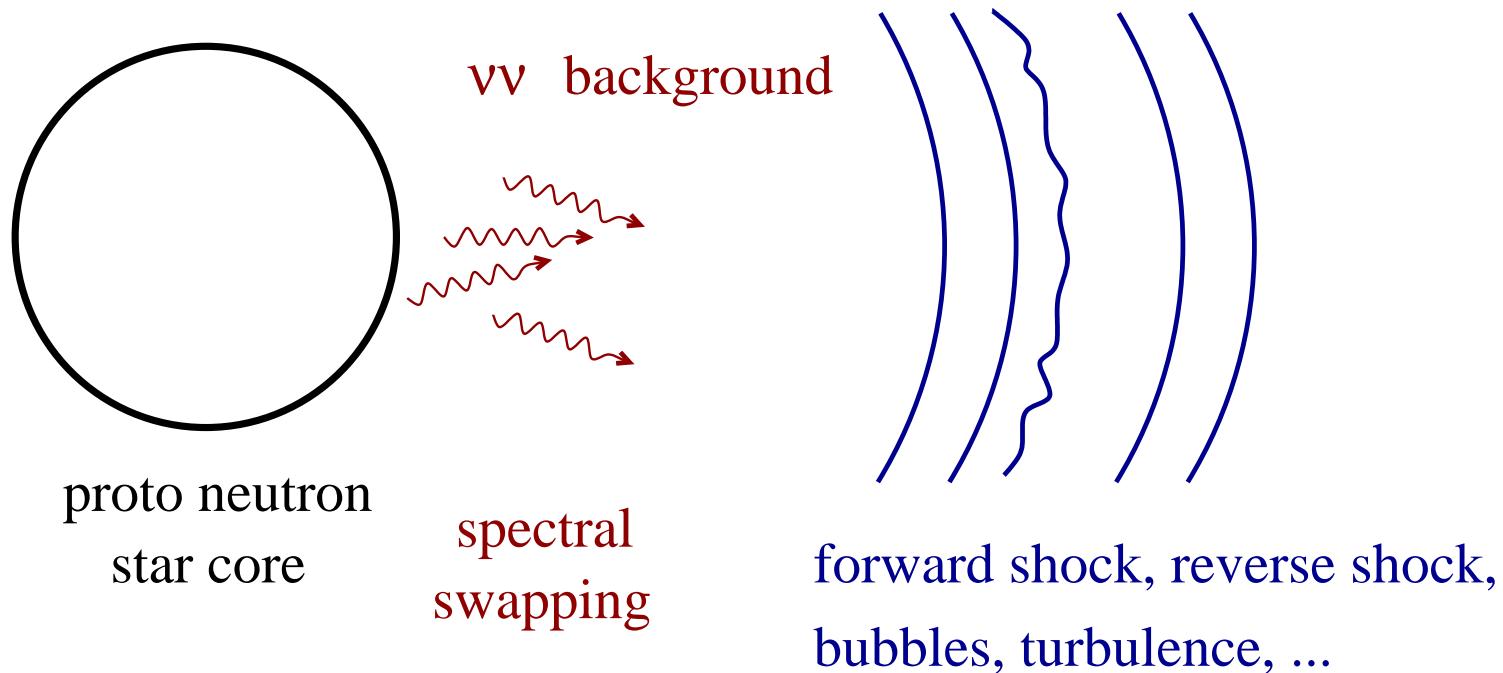
Old picture of supernova neutrino transformation

Static density profiles, collective effects not included...



Primary uncertainties in evolution: Hierarchy, θ_{13} e.g. Dighe and Smirnov 2000

New picture of supernova neutrino transformation



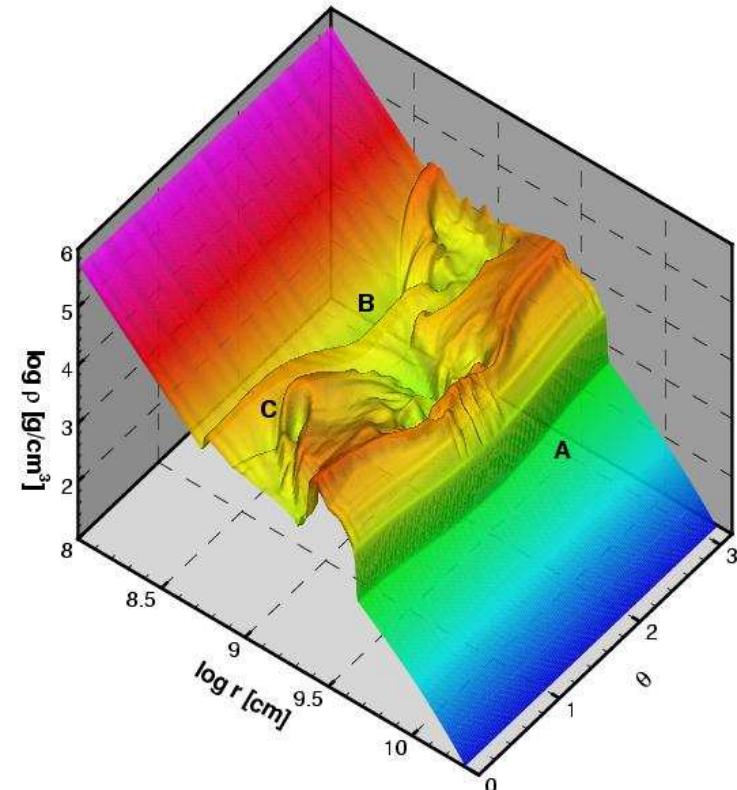
Many more possibilities, depending on: hierarchy, θ_{13} , evolution of density profile

Neutrino evolution calculations much more complex

What can SN neutrinos probe?

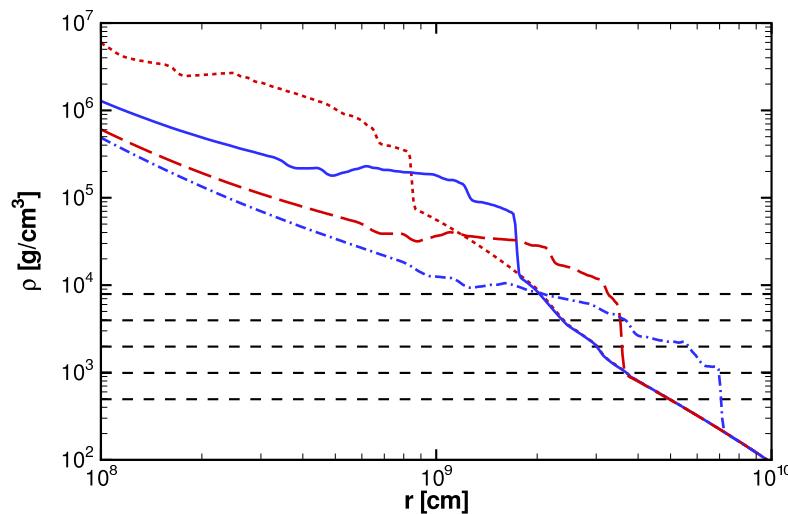
Supernova Hydrodynamics

- initial density profile
- forward/reverse shocks
- “bubbles”, turbulence



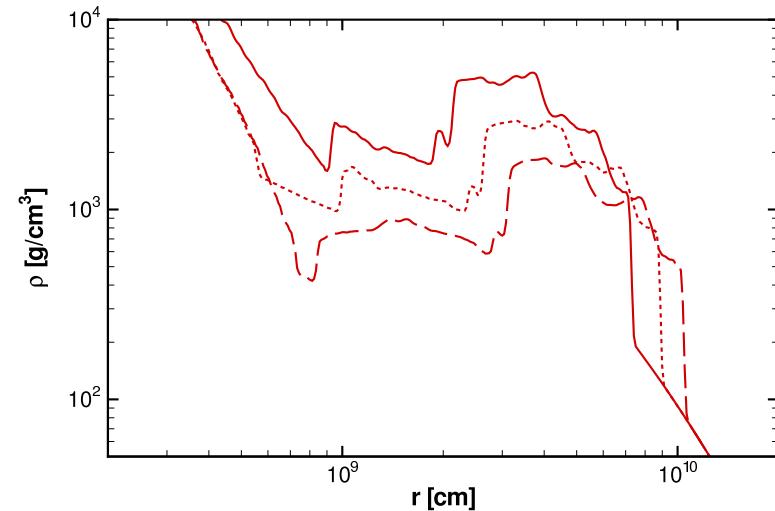
Density profile from a SN toy model at 2.5s, Kneller et al 2008

Supernova Hydrodynamics



Density slices at 0.9s, 1.8s, 3.6s and 7.2s from a 1D toy model.

Horizontal dashed lines show resonances densities for 5 MeV,
10 MeV, 20 MeV, 40 MeV and 80 MeV.
 $Q = 1.66 \times 10^{51}$ ergs



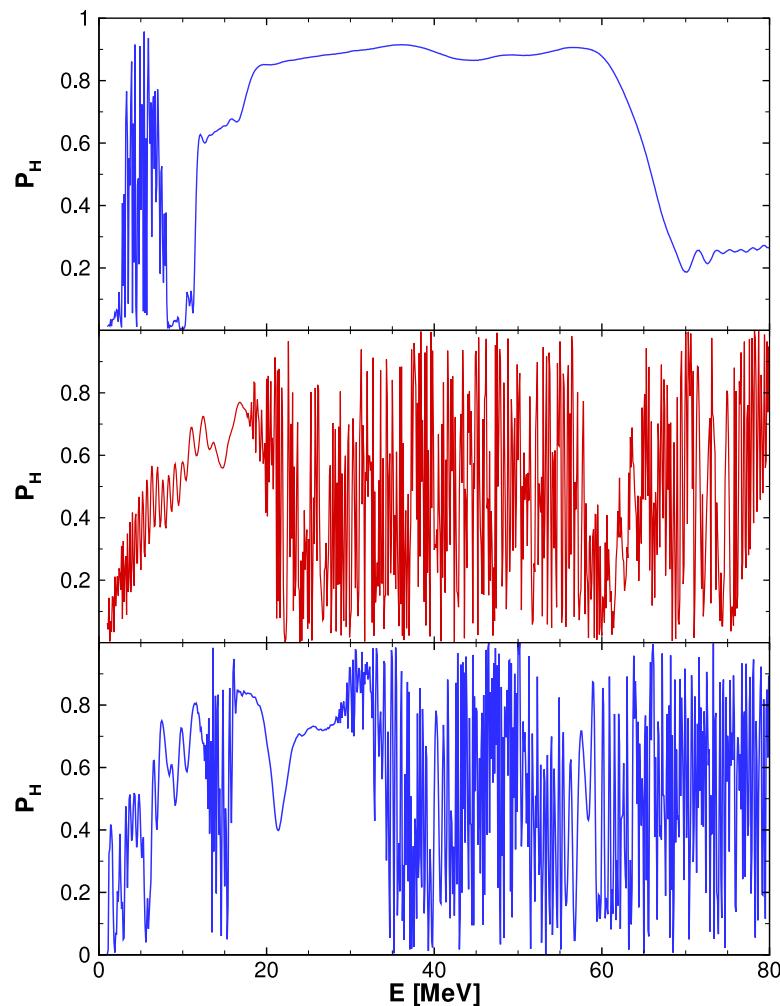
Density slices at 3.9s, 4.8s and 5.7s from a 2D toy model

$Q = 3 \times 10^{51}$ ergs

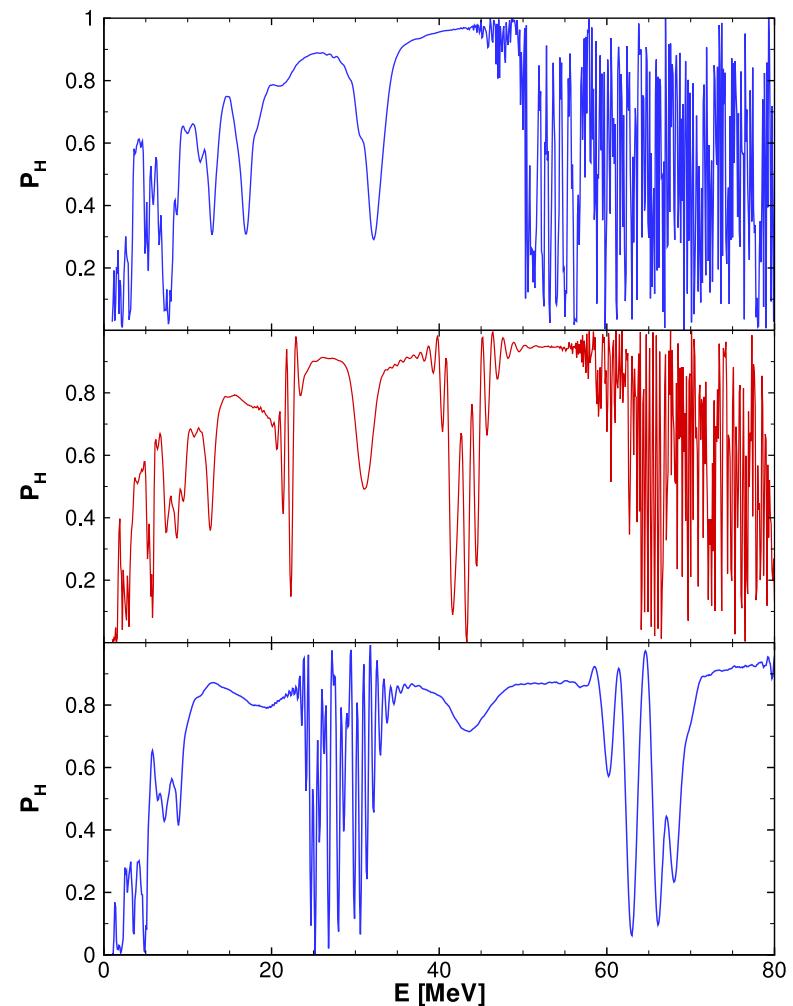
Figures from Kneller et al 2008

Matter-enhanced neutrino oscillations depend on the density
structure...

Finely grained phase effects due to density perturbation



H resonance crossing probability at 2.4s, 5.4s, 6.4s,
 $\delta m^2 = 10^{-4}$, $\sin^2 \theta_{13} = 10^{-1}$

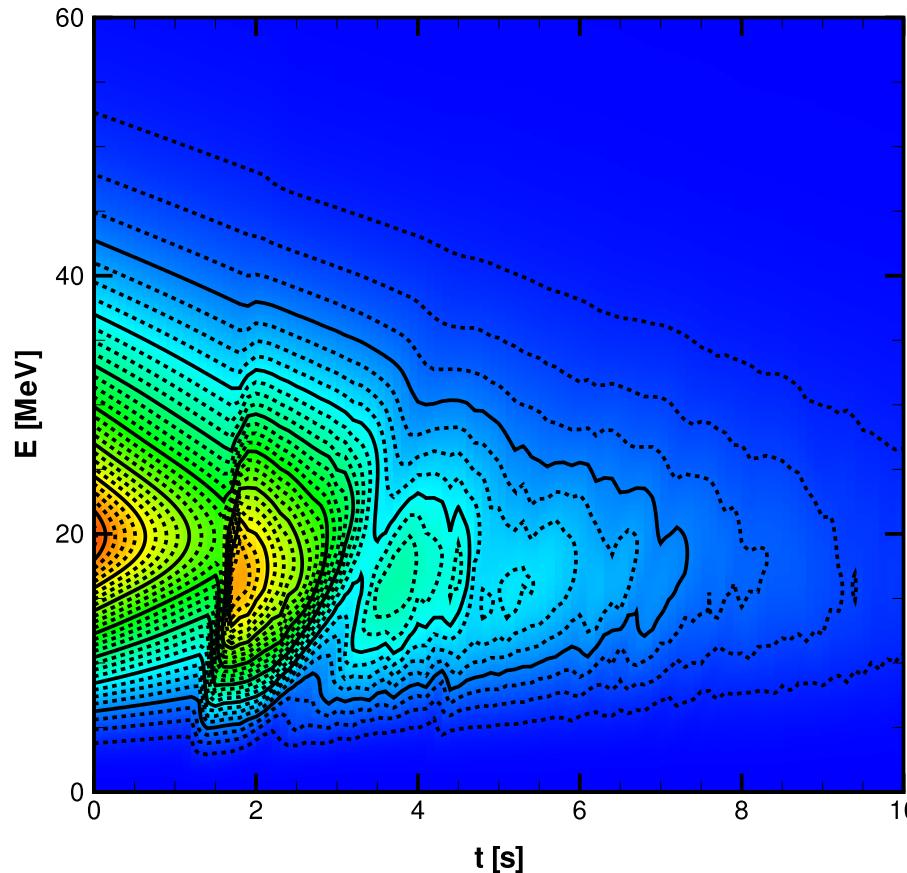


H resonance crossing probability at 7.0s, 8.0s and 9.0s,
 $\delta m^2 = 10^{-4}$, $\sin^2 \theta_{13} = 10^{-1}$

Rapid oscillation as a fct of energy is indicative of multiple resonances

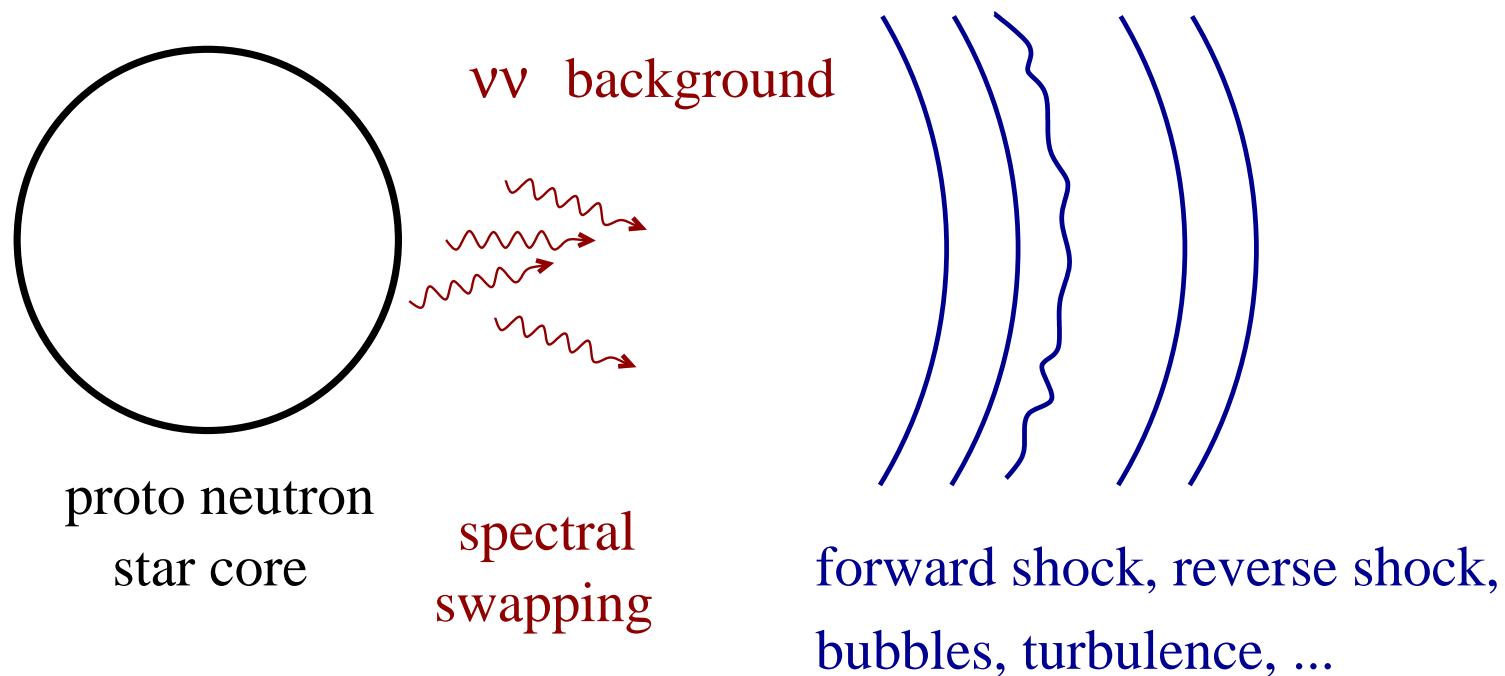
Measuring a Galactic supernova neutrino signal

Positron spectrum in a water detector



Shows the forward shock and “phase effects” due to multiple resonances, collective effects not included, units of $10^{-3} / \text{MeV/s}$ /
Kneller et al 2008

New Picture of Supernova Neutrino Transformation



Many more possibilities, depending on: hierarchy, θ_{13} , evolution of density profile

Neutrino evolution calculations much more complex

Collective effects, single angle

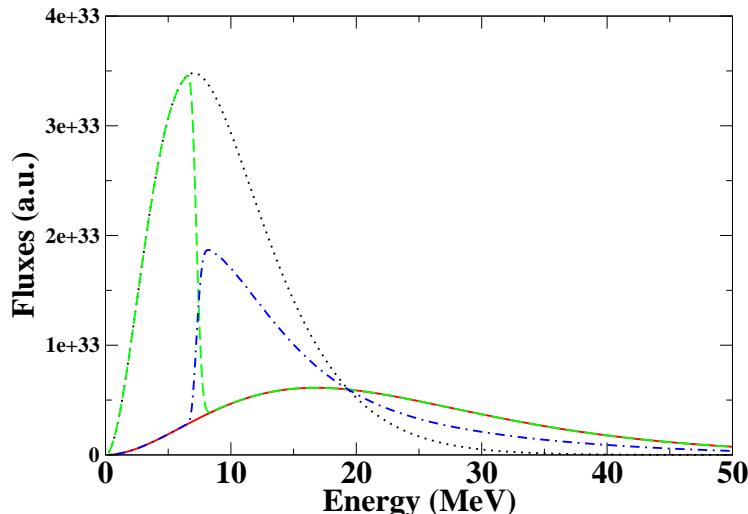
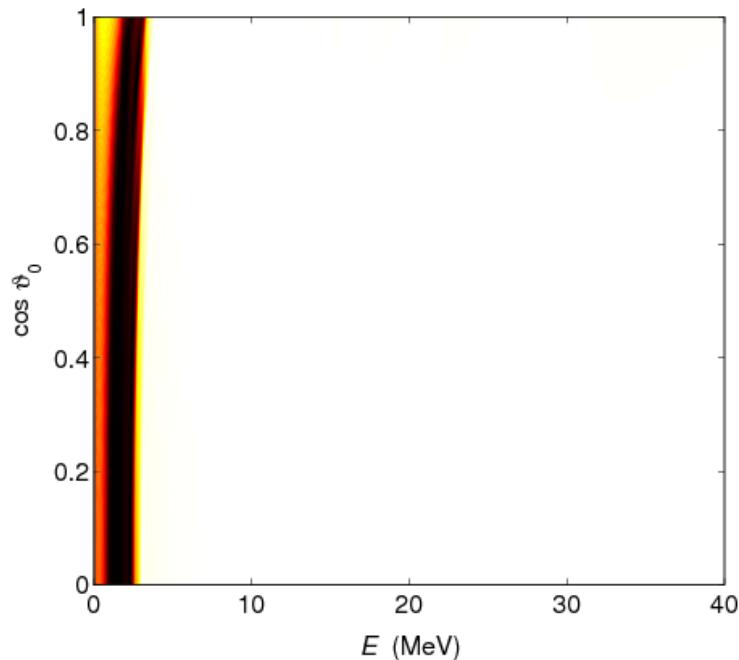


Figure from Gava and Volpe 2008

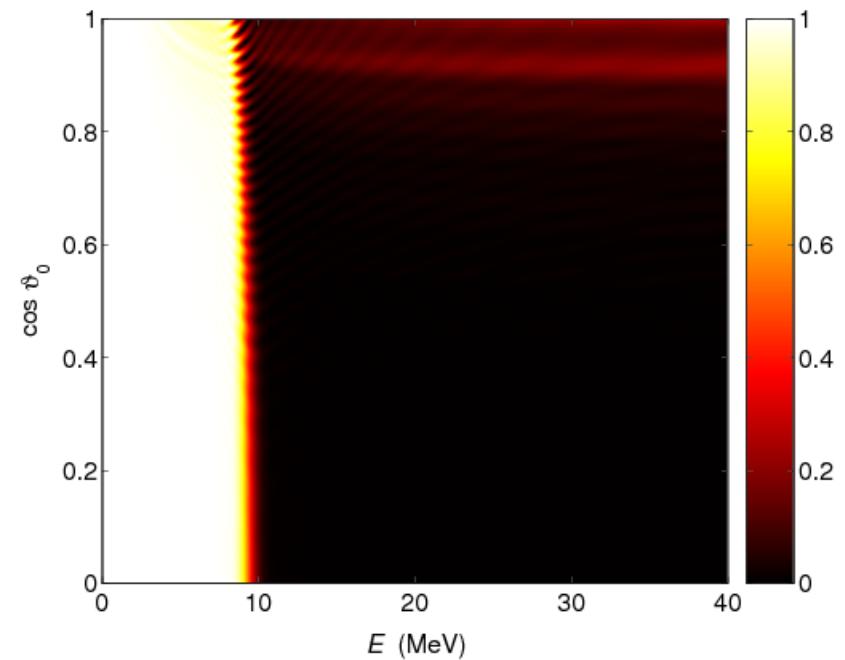
- ν - ν scattering potential included in flavor transformation calculation
- occurs far below traditional resonances

Shows ν_e , ν_μ spectra as emitted and at 200km, “Spectral Split”

Collective effects, multi-angle



Neutrino Survival Probabilities as a function of emission angle (vertical axis). Normal mass hierarchy, with $\theta_\nu = 0.01$.



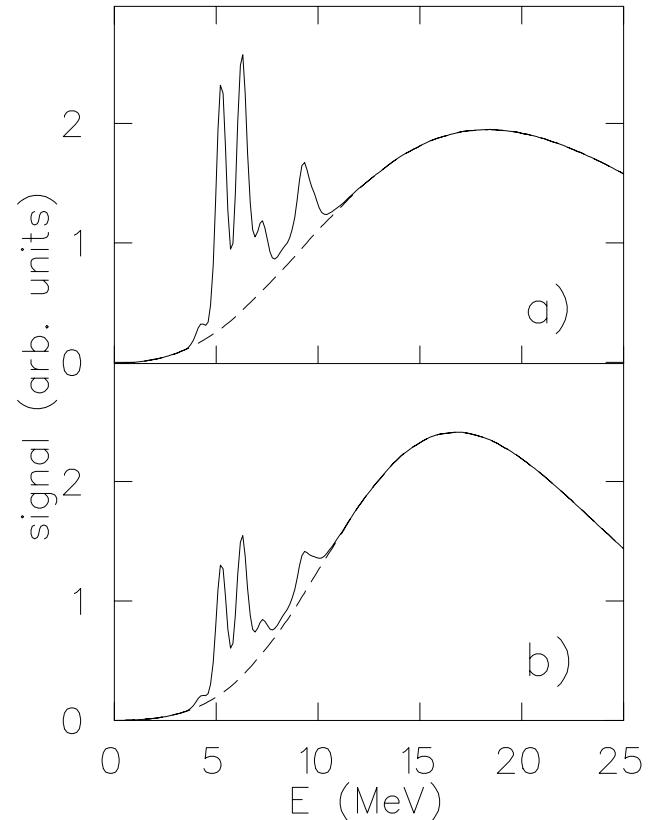
Antineutrino survival probabilities.
Inverted mass hierarchy with $\theta_\nu = 10^{-9}$

Figures from Duan, Fuller, Qian 2008

Measuring a Galactic supernova neutrino signal

Neutral current

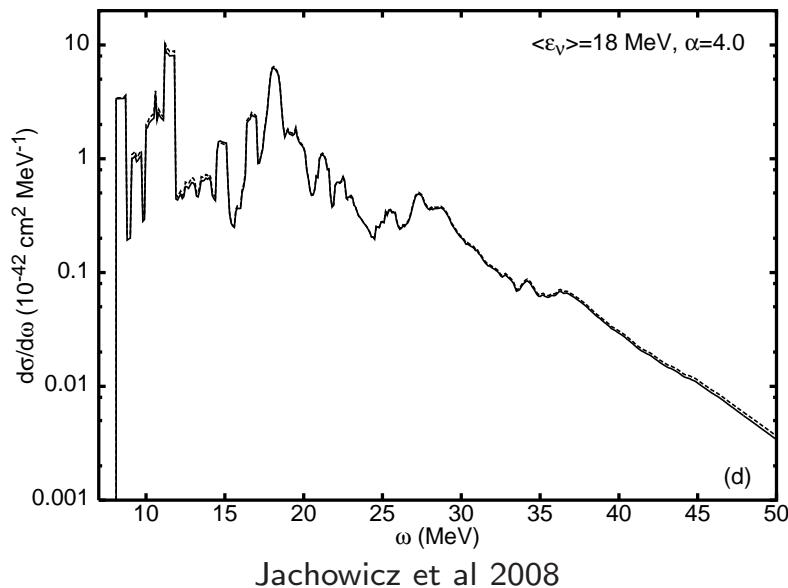
- water detector: $\bar{\nu}_e + p \rightarrow n + e^+$
- $\nu_x + {}^{16}\text{O} \rightarrow {}^{15}\text{N} + p + \nu_x$
 $\nu_x + {}^{16}\text{O} \rightarrow {}^{15}\text{O} + n + \nu_x$
- LAr $\nu_x + {}^{40}\text{Ar}$
- lead detector (e. g. HALO):
 $A(\nu_e, e)A'$ & neutral current channels



Signal (γs) in a Water Detector, Kolbe et al 2003
bump: from e^+ s, peak: decays from ${}^{15}\text{O}$, ${}^{15}\text{N}$

And many more possibilities including, neutrino-nucleus coherent scattering, neutrino-nucleus inelastic scattering

Cross section data is needed



Jachowicz et al 2008

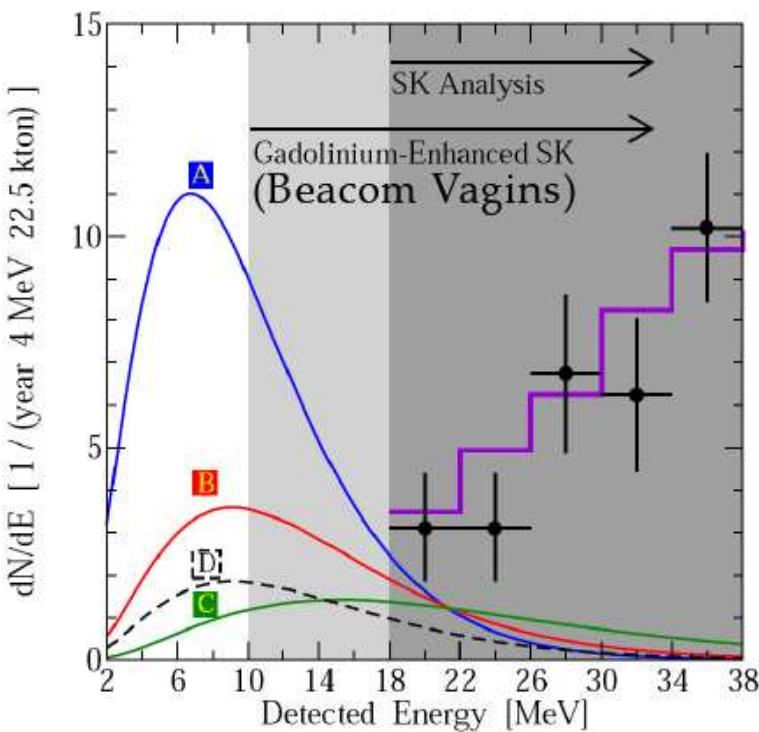
- e.g. ν -SNS, proposed for ORNL
- and low energy β beams

Figure: linear combination of neutrino-nuclear responses from beta beam spectra can be used to reproduce that of SN neutrinos.

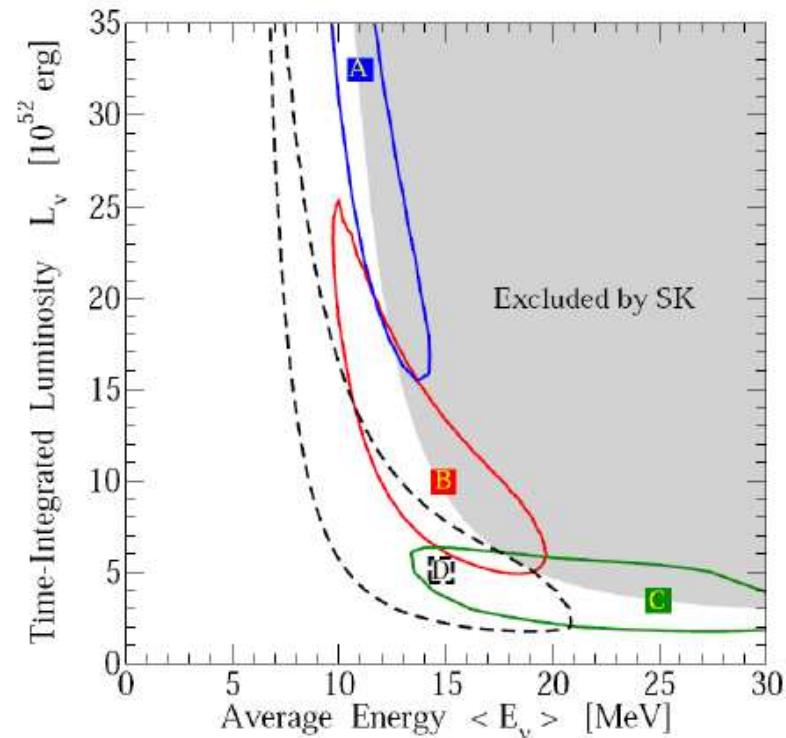
Diffuse Supernova Neutrino Background

DSNB Limits/Prospects

Super-K Limit: $1.2 \text{ cm}^{-2} \text{ s}^{-1}$ ($>18 \text{ MeV}$)



Yüksel Ando Beacom



- Constraints on the time-integrated luminosity and average energy may also constrain the explosion energy and protoneutron star opacity

Talk by Hasan Yüsel

Conclusions: What we hope to learn from a future SN neutrino signal

- Something about the core
- Something about supernova hydrodynamics
- Something about neutrino spectra as emitted from the core
- Something about fundamental neutrino properties

There will be degeneracies... but still new data is eagerly awaited...